AN ANALYSIS OF POTENTIAL MARKETS

AND THEIR FUEL REQUIREMENTS

FOR AN IN-SPACE PROPELLANT DEPOT

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INTRODUCTION

An on-orbit propellant depot has been proposed as a potentially cost-savings solution to satellite and potential space transport fuel requirements. As a first step in a realistic economic benefit analysis, Futron Corporation undertook the study described herein to assess a depot's potential markets and their associated fuel requirements. Economies of scale realized by aggregating quantities of propellant on orbit could create an economic argument for the existence of such a depot, offsetting the costs of depot operations for other, non-business applications such as fueling a human Mars mission. This work was carried out under contract to the NASA Marshall Space Flight Center (MSFC), NAS8-99134.

THE REFERENCE PROPELLANT DEPOT

The propellant depot referenced in this analysis would be deployed in a 400 km circular equatorial orbit. The depot would store and transfer liquid oxygen (LOX) and liquid hydrogen (LH2) to transfer vehicles which would in turn maneuver a satellite or platform as required. This analysis is valid for both a depot that receives the separate components of the cryogenic propellant and one that receives water ice and converts the compound into LOX/LH2 via electrolysis. For this analysis, the maneuvering and transferring vehicles were configured after the Delta IV-H Upper Stage, which can handle up to 27 metric tons of propellant and has a 5.5:1 oxidizer to fuel ratio.[1]

MARKET STUDY PARAMETERS

This study consisted of an initial canvassing of potential markets for a propellant depot, a systematic evaluation of candidate markets for technical feasibility, and a quantitative fuel requirements analysis for surviving markets.[2]

Near-term potential markets for a propellant depot include variations on:
- Orbital station keeping
    o Geosynchronous (GSO) and low-Earth orbit satellites
        - Commercial
        - Government
    o Emerging markets crewed and robotic orbital platforms
- Orbital maneuvering
    o LEO to GSO transfer
    o GSO orbit change
    o LEO orbit change
    o Satellite recovery
- Extra-orbital vehicle fueling

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[1] Steven J Isakowitz, *International Reference Guide to Space Launch Systems, Second Edition*, Washington, DC: American Institute of Aeronautics and Astronautics, 1995.

[2] See Appendix A for a broad discussion of markets potentially enabled by the presence of an orbital fuel depot.

Futron subjected these markets to a depot-use feasibility model to eliminate those markets for which depot use was not a technically viable option within the study's 20-year time frame (2000-2020).

Within the twenty-year time period addressed in this study, the extra-orbital vehicle fueling market (e.g., interplanetary transports, crewed and uncrewed), if realized, would in all likelihood consist of government-sponsored missions to the Moon, Mars, or other inner solar system destinations. The propellant requirements for the most challenging of these scenarios, a Mars mission, have been explored in earlier studies and are therefore not addressed here.[3]

Futron's analysis of satellite bus propellant systems revealed commercial and government satellite station keeping as an unlikely market for this configuration of a propellant depot. Given the precise orbit maintenance requirements of most satellites today, along with system and storage requirements for the proposed depot propellant system, liquid Hydrogen/liquid Oxygen (LH2/LOX), no major satellite manufacturer currently uses or proposes to use LH2/LOX for station keeping. This analysis therefore excludes estimates for GSO and LEO station keeping for traditional, discrete satellites.

Recovery of satellites is another potential market for a propellant depot. However, given the relatively infrequency with which satellites are delivered to sub optimal orbits, this market represents only nominal propellant requirements, adding at the outer envelope 1 to 2 GSO transfer equivalents a year. While the market value of these recoveries may be high, they do not represent a driving requirement for propellant sizing.

Markets surviving the vetting process and meriting quantitative assessment for the propellant depot include:

1. LEO to GSO transfer for both government and commercial markets
2. Reboost for emerging markets

Large fuel requirements for satellite transfer from LEO to GSO make this market perhaps the most likely commercial user of a propellant depot. This market is characterized by the delivery of a satellite to the Depot orbit and the ferrying of the satellite to GSO by an orbital transfer vehicle (OTV). Moreover, the multi-module nature of emerging market platforms, along with their likely low dependence upon precision orbit maintenance (unlike commercial communications satellites) make periodic reboost by a visiting orbital maneuvering vehicle (OMV) a viable technical option for these assets. In order to determine the propellant required for each of these markets, Futron first forecasted the 20-year demand for the orbital assets, calculated the ΔV required to carry out the indicated maneuvers, and then figured the total propellant required given reference technical specifications of the propellant, OTV, and OMV.

SIZING POTENTIAL MARKETS FOR THE PROPELLANT DEPOT

GSO TRANSFER

The GSO transfer market includes both commercial and governmental satellites being launched over the next twenty years. The commercial satellites include traditional and emerging telecommunications applications; the governmental satellites include both military and civil applications globally.

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[3] The Boeing Company, *Space Solar Power Platform Technologies for In-Space Propellant Depots, Final Report* (under contract to NASA, Contract # NAS8-99140, Mod 2, Task 3), November 14, 2000.

COMMERCIAL SATELLITES

Commercial GSO Telecommunications Forecast Methodology

Each year Futron develops a demand-based forecast of commercial GSO telecommunications satellites. This forecast is a country-by-country analysis of the underlying demand for telecommunications satellites, the ability of the country to afford such services, and the competitive position of the satellite industry to provide such services. This analysis relies on Futron's 2000 Annual Commercial GSO Forecast, extended through 2020.

This forecasting methodology is unique in that it relies on the demand for telecommunications services and includes all current and emerging applications of satellites. The Futron model considers the competitive strengths and weaknesses of satellites and competing terrestrial services for each application in terms of price, service quality, availability, and other factors. The model also explicitly considers the effect of the political and regulatory environment and the impact of technology developments such as digitization, data compression, increased satellite life, increased number of transponders per satellite, and increased bandwidth per transponder.

Telecommunications services included in the 2000 forecast fall into three broad categories:

Telephone
- Telephone trunking
- End-user satellite telephony
- Wireless telephone services

Television
- Broadcast and Cable television relay
- Direct-to-home services

Data communications
- VSAT
- End-user internet
- Internet backbone
- Asset management
- Advanced data communications: cashing, media casting and airborne telecommunications

Commercial GSO Telecommunications Forecast

Commercial GSO satellites comprise about 2/3 of the total GSO forecast. The forecast projects satellites to both meet new demand and replace existing satellites as they come to their expected end-of-life. The chart in Figure 1 shows much year-to-year variation that will, in all likelihood, be somewhat smoothed due to the reality of launch manifesting and throughput capacity. What is important is the average number of satellites launched as well as the number of satellites launched in each mass class (since mass will affect propellant requirements). On average, 24 satellites are launched each year. Although most of the satellites fall into the intermediate mass class, Figure 1 shows the number of medium weight satellites decreasing and large weight satellites increasing as the average size of satellites increases over the forecast period.

FIGURE 1. COMMERCIAL GSO SATELLITE LAUNCH FORECAST, 2001-2020, BY SATELLITE MASS CLASS[4]
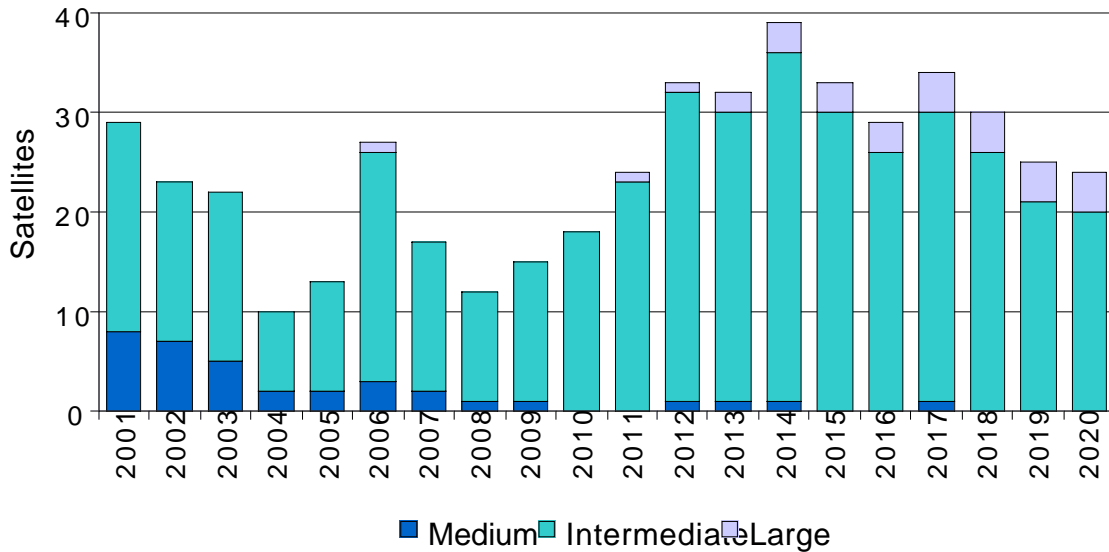
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Microsat	0	0	0	0	0	0	0	0	0	0
Small	0	0	0	0	0	0	0	0	0	0
Medium	8	7	5	2	2	3	2	1	1	0
Intermediate	21	16	17	8	11	23	15	11	14	18
Large	0	0	0	0	0	1	0	0	0	0
Heavy	0	0	0	0	0	0	0	0	0	0

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Microsat	0	0	0	0	0	0	0	0	0	0
Small	0	0	0	0	0	0	0	0	0	0
Medium	0	1	1	1	0	0	1	0	0	0
Intermediate	23	31	29	35	30	26	29	26	21	20
Large	1	1	2	3	3	3	4	4	4	4
Heavy	0	0	0	0	0	0	0	0	0	0

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[4] Satellite mass classes are defined by the FAA as:
    Microsat <200 lbs.
    Small 201 to 2000 lbs.
    Medium 2001 to 5000 lbs.
    Intermediate 500 to 10,000 lbs.
    Large 10,001 to 20,000 lbs.
    Heavy > 20,000 lbs

GOVERNMENT

Government GSO Forecast Methodology

In addition to a commercial satellite forecast, Futron also uses a proprietary methodology for forecasting government satellites. Unlike commercial satellites, government missions are not market driven; in order to develop an accurate forecast, Futron researches and analyzes past trends and future plans of government space programs worldwide.
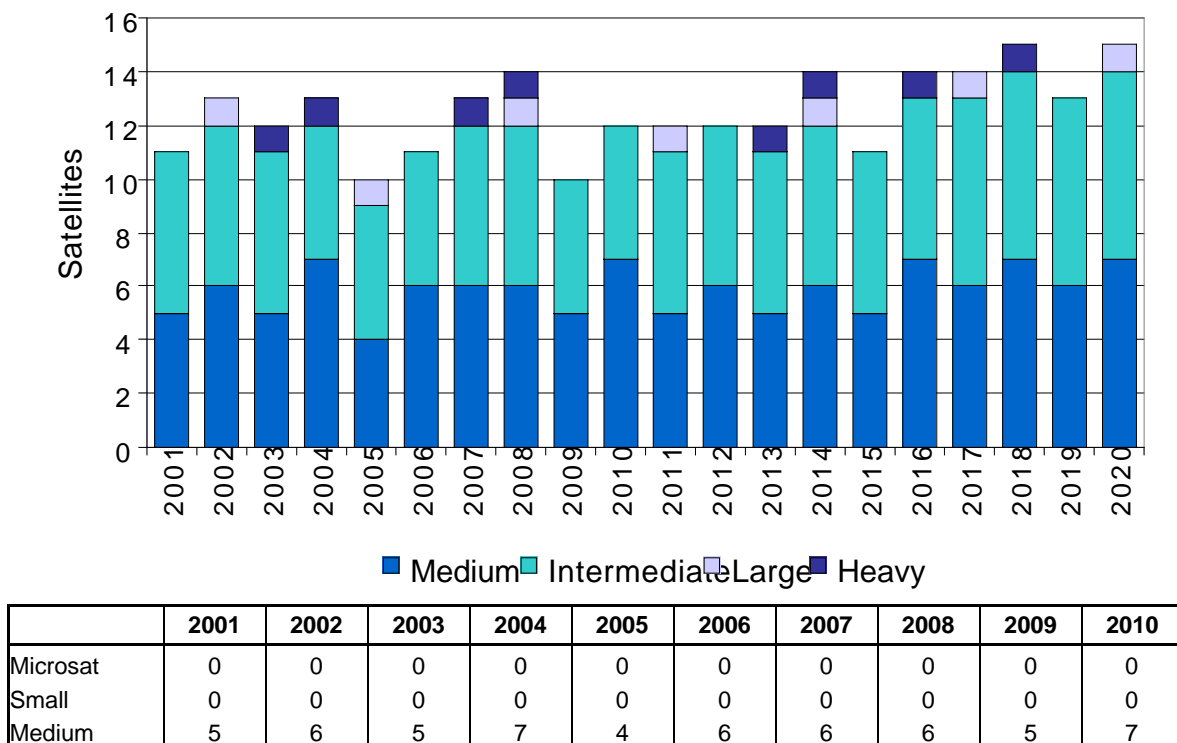
The basis of the U.S. government forecast is the National Launch Forecast from the United States Air Force. This document is regularly updated and contains every launch and payload expected by the United States for the next 10 years. Futron projected these trends through 2020 for the purposes of this analysis.

To develop forecasts of government launch activity for the rest of the world, Futron first uses its proprietary launch activity database, the Electronic Library of Space Activity (ELSA), to gather information about planned government payloads. ELSA is constantly being kept up to date by a process that requires extensive research of all relevant literature, discussions with program participants, and internal Futron analysis. Futron then uses analysis of past trends and planned government budgets to project their planned launch activities through the forecast period.

Government GSO Forecast

The forecast for new government satellites is fairly constant, ranging between 11 and 15 satellites per year through 2020, which is consistent with global patterns of government space spending. Government satellites comprise about 1/3 of the total GSO market forecast.

FIGURE 2. GOVERNMENT GSO SATELLITE LAUNCH FORECAST, 2001-2020, BY SATELLITE MASS CLASS

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Microsat	0	0	0	0	0	0	0	0	0	0
Small	0	0	0	0	0	0	0	0	0	0
Medium	5	6	5	7	4	6	6	6	5	7

Intermediate	6	6	6	5	5	5	6	6	5	5
Large	0	1	0	0	1	0	0	1	0	0
Heavy	0	0	1	1	0	0	1	1	0	0

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Microsat	0	0	0	0	0	0	0	0	0	0
Small	0	0	0	0	0	0	0	0	0	0
Medium	5	6	5	6	5	7	6	7	6	7
Intermediate	6	6	6	6	6	6	7	7	7	7
Large	1	0	0	1	0	0	1	0	0	1
Heavy	0	0	1	1	0	1	0	1	0	0

LEO REBOOST

The LEO reboost market incorporates both crewed and uncrewed on-orbit platforms that require only gross altitude maintenance. While the International Space Station falls into this category, its existing configuration is incompatible with the reference OMV and so does not appear in this forecast. The emerging markets forecast incorporates any potential follow-on to the International Space Station.

EMERGING MARKETS

Emerging Markets Forecast Methodology

Futron has developed an emerging markets forecast based on data from the Commercial Space Transportation Study (CSTS). While the CSTS data are limited in many respects, the study is the most comprehensive and quantitative to date. Futron updated and revised the CSTS data in late 2000 with information and market insight garnered since the 1994 CSTS study, and this analysis uses those revised projections. Futron also added enhanced price elasticity curves to allow analysis of emerging markets at different price points. At the current price per pound to LEO ($4000), it is not economically feasible for these markets to surface; therefore this analysis studies both crewed and uncrewed platforms at two lower price points: $1000/pound and $500/pound. The $1000/pound to orbit figure represents the 20-year goal of NASA's 2nd Generation Space Transportation Program. The order of magnitude reduction from current prices to $500/pound represents envisioned performance of a 3rd generation space transportation system.

The following markets from CSTS have been included in this forecast:

Crewed
- Space Athletic Event
- Theme Park
- LEO Business Park

Uncrewed
- Space Manufacturing
- Orbiting Movie Studio
- Utilities
- SSP
- Space Testbed

Emerging Markets Forecast at $1000/pound

At this price point there is no market for crewed on-orbit platforms (beyond the International Space Station). However, at $1000 per pound a modest market for *uncrewed* platforms surfaces in 2008. After 2008, the on-orbit mass of emerging markets' uncrewed platforms increases by an average of 25% each year through 2020.

FIGURE 3. UNCREWED PLATFORM FORECAST OF CUMULATIVE POUNDS ON ORBIT AT $1000/POUND, 2001-2020
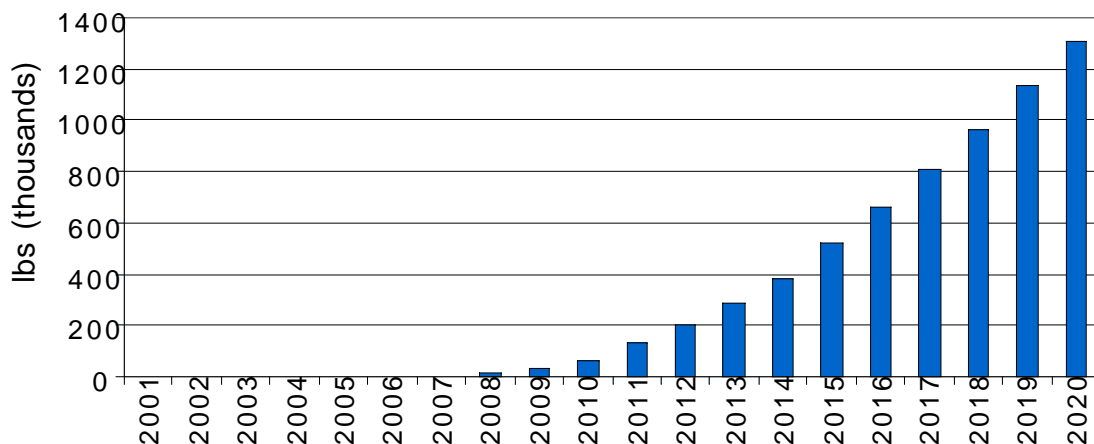
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cumulative lbs on orbit	0	0	0	0	0	0	0	14,432	34,168	66,107

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Cumulative lbs on orbit	128,914	202,220	287,214	381,371	518,945	660,696	811,825	967,626	1,134,293	1,306,126

Forecast at $500/pound

At $500 per pound, both crewed and uncrewed platforms become feasible markets. However the uncrewed market is much larger than the crewed market.

In the crewed market forecast, the analysis uses the *Soyuz* capsule as a reference point for the minimum mass (7,000 lbs) of a self-sustainable, crewed orbital element. The forecast therefore constrains the crewed markets from surfacing until the orbital assets meet this minimum mass.

FIGURE 4. CREWED PLATFORM FORECAST OF CUMULATIVE POUNDS ON ORBIT AT $500/POUND, 2001-2020
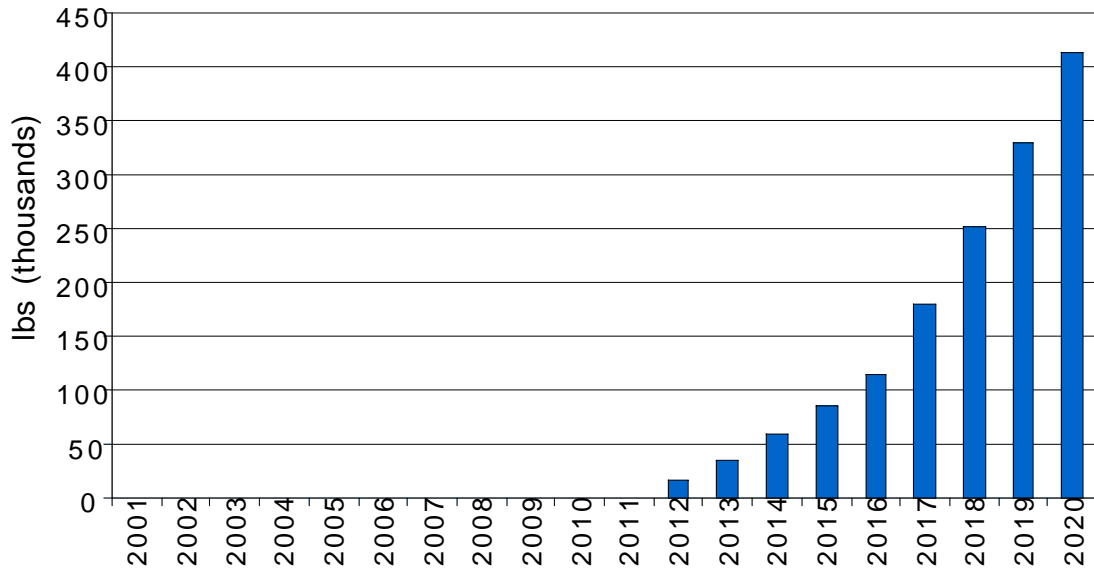
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cumulative lbs on orbit	0	0	0	0	0	0	0	0	0	0

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Cumulative lbs on orbit	0	15,852	35,434	58,747	85,167	114,696	179,969	251,460	329,167	413,090

The Progress vehicle weighs 7,000 lbs at launch, therefore the 17,000 lbs launched in 2008 is reasonable.

FIGURE 5. UNCREWED PLATFORM FORECAST OF CUMULATIVE POUNDS ON ORBIT AT $500/POUND, 2001-2020
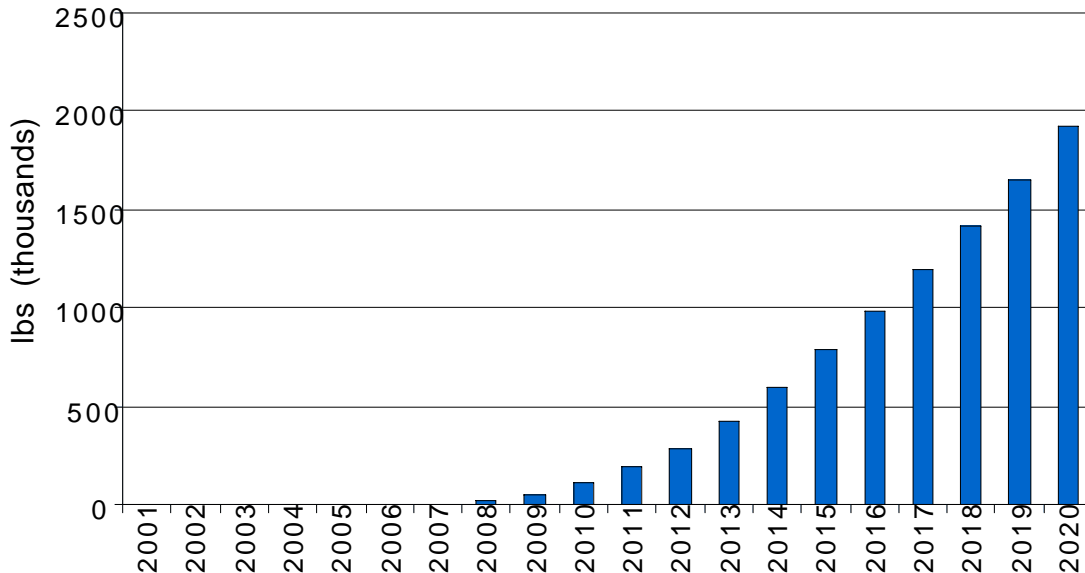
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cumulative lbs on orbit	0	0	0	0	0	0	0	17,002	45,912	112,291

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Cumulative lbs on orbit	189,054	279,986	429,552	601,015	785,158	983,466	1,189,630	1,412,186	1,652,618	1,923,538

MARKET FUEL REQUIREMENTS

FUEL ESTIMATING METHODOLOGY

Calculation of the propellant required to ferry a satellite from one orbit to another relies upon a number of factors, including: the parameters of both orbits, the mass of the satellite and OTV/OMV, and select parameters of the OTV/OMV motor which affect specific impulse. Given the appropriate inputs, the ΔV of the orbital maneuver and, subsequently, the appropriate mass of propellant can be calculated.

GSO TRANSFER METHODOLOGY

The known orbital parameters of the LEO to GSO transfer facilitate a round trip propellant requirements calculation. The GSO transfer propellant analysis therefore calculates the propellant required to maneuver a satellite from a 400-km circular, equatorial orbit to GSO by means of an OTV and return the OTV to the depot to refuel and await the next payload.

The GSO satellite forecast was broken out into satellite mass classes. The allocation of satellites to these mass classes changes over the forecast period, in general allocating more satellites to the larger mass classes commensurate with exhibited trends in satellite technologies and architectures. Since the propellant calculation requires payload mass as an input variable,

satellites were assigned the mean mass of their given mass class. Since there is no maximum mass for the heavy class, the average mass was found using the minimum mass for the class and the 4 heavy payloads that have been launched to GSO since 1985.
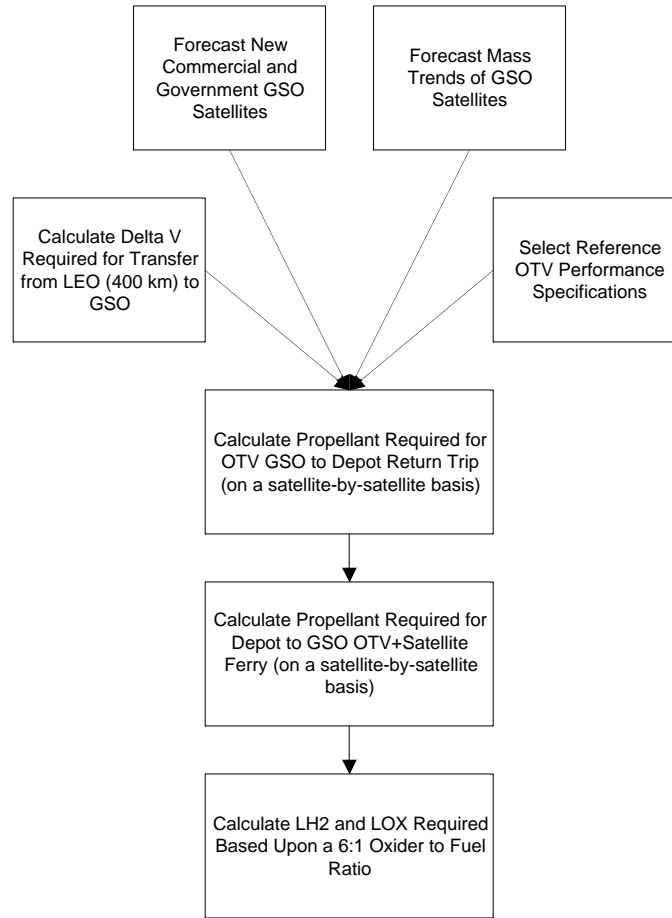
FIGURE 6: SATELLITE MASS CLASS

Satellite Mass Class	Capacity (lbs)	Mean Mass (lbs)
Microsat	0-200	100
Small	201-2000	1101
Medium	2001-5000	3501
Intermediate	5001-10,000	7501
Large	10,001-20,000	15,001
Heavy	20,001 +	27,847

The following flowchart (Figure 7) shows the overall approach applied to calculating the amount of LOX and LH2 required to complete the maneuver successfully.

For each satellite, the transfer maneuver's required velocity change (delta V, or ΔV), the satellite mass, and the OTV's performance specifications feed into the propellant calculation. Figure 7 exhibits the overarching methodology to calculate the propellant required to service the GSO transfer market.

FIGURE 7: GSO TRANSFER MARKET PROPELLANT REQUIREMENTS METHODOLOGY

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┌─────────────────┐   ┌─────────────────┐
│ Forecast New    │   │ Forecast Mass   │
│ Commercial and  │   │ Trends of GSO   │
│ Government GSO   │   │ Satellites      │
│ Satellites      │   │                 │
└─────────────────┘   └─────────────────┘

┌─────────────────┐   ┌─────────────────┐
│ Calculate Delta V│  │ Select Reference │
│ Required for     │  │ OTV Performance  │
│ Transfer from    │  │ Specifications   │
│ LEO (400 km) to  │  │                  │
│ GSO              │  │                  │
└─────────────────┘   └─────────────────┘

┌──────────────────────────────────────┐
│ Calculate Propellant Required for     │
│ OTV GSO to Depot Return Trip          │
│ (on a satellite-by-satellite basis)   │
└──────────────────────────────────────┘

┌──────────────────────────────────────┐
│ Calculate Propellant Required for     │
│ Depot to GSO OTV+Satellite            │
│ Ferry (on a satellite-by-satellite    │
│ basis)                                │
└──────────────────────────────────────┘

┌──────────────────────────────────────┐
│ Calculate LH2 and LOX Required        │
│ Based Upon a 6:1 Oxider to Fuel       │
│ Ratio                                 │
└──────────────────────────────────────┘
```

Total ΔV required to transfer a payload from the 400-km circular, equatorial orbit of the propellant depot to the geosynchronous orbit of 35,782 km is necessary to calculate the mass of propellant and can be found with the following formula:[5]

$$\Delta V = \sqrt{\mu} \left[\left| (2/r_a - 1/a_{tx})^{-} - (1/r_a)^{-} \right| + \left| (2/r_b - 1/a_{tx})^{-} - (1/r_b)^{-} \right| \right]$$

where:

r_a = 6778 km, distance from the Earth's center for 400-km orbit
r_b = 42,160 km, distance from the Earth's center for GSO orbit
$a_{tx} = (r_a + r_b)/2$
μ = 398,600.5 km^3/sec^2

Therefore, ΔV = 3.86 km/sec to transfer a satellite from the propellant depot to its GSO location, presuming the use of a Hohmann transfer, the most fuel-efficient transfer between two circular, coplanar orbits.

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[5] All formulae and orbital constants are drawn from James R. Wertz and Wiley J Larson, eds., *Space Mission Analysis and Design*, London: Kluwer Academic Publishers, 1991. *errata* included.

FIGURE 8: THE HOHMANN TRANSFER GEOMETRY
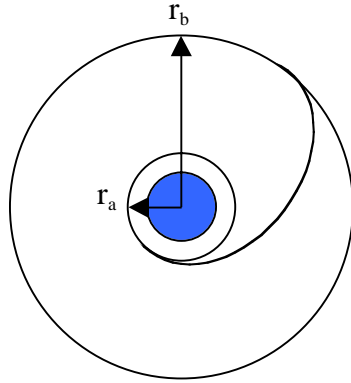
The OTV carries the satellite from the depot to GSO and then must return itself to the depot to refuel and await the next payload. The OTV must carry enough propellant for the round trip. The necessary propellant can be calculated in two steps:

1) propellant required for the OTV to travel from GSO back to the depot, and
2) propellant required for the OTV to boost the satellite to GSO.

In the case of step 1), the propellant mass formula is as follows:

$$m_{pr} = m_d \, [e^{(\Delta V / I_{sp} g)} - 1]$$

where:
m_{pr} = mass of propellant required to transfer OTV from GSO to 400-km equatorial
m_d = 3490 kg (dry mass of Delta IV H)
ΔV = 3.86 km/sec, velocity change required between GSO and 400-km equatorial
I_{sp} = 462.4 sec, specific impulse of the Delta IV H
g = 0.0098 km/sec^2, Earth's gravitational acceleration constant at sea level

In the case of step 2) above:

$$m_p = m_f \, [e^{(\Delta V / I_{sp} g)} - 1]$$

m_p = mass of propellant required to transfer OTV and satellite from 400-km equatorial to GSO
m_f = $m_d + m_w + m_{prm}$, the total mass of the OTV and its payload on the trip to GSO, excluding the propellant required for LEO to GSO transfer
m_{prm} = $1.25 m_{pr}$ (to allow for margin)
m_w = wet mass of satellite

Presuming a 6:1 oxidizer-to-fuel mass ratio (although the Delta IV-H actually uses a 5.5:1 ratio), the mass requirements for LOX and LH2 can be determined.

This analysis represents the minimum requirements for a propellant depot to service the GSO transfer market in its entirety, presuming the existence and use of the orbital transfer vehicle (OTV) by all GSO satellites. In practice, it is likely more efficient for the satellites to be delivered to inclined LEO orbits rather than an equatorial orbit and for the OTV to "fetch" these satellites from their initial orbits before shuttling them up to GSO. This maneuver would involve
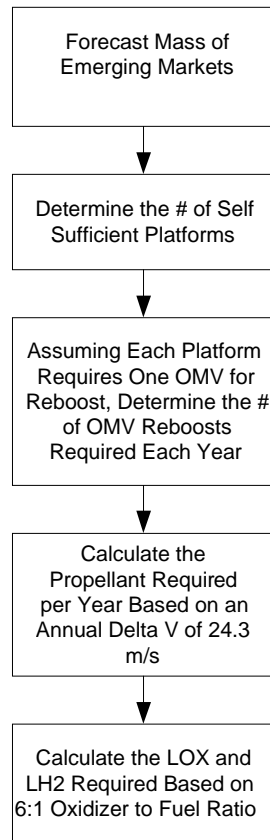
at least two plane changes for the OTV and the satellite, and so would represent a greater ΔV than calculated herein and hence more propellant.

LEO REBOOST METHODOLOGY

The LEO reboost market requires the OMV to travel to and from the orbital asset, performing the reboost maneuver on the asset in between. However, unlike the GSO transfer analysis, no single reference destination orbit exists on which to base general calculations. The calculations for the LEO reboost market, then, estimates only the propellant required to maintain the assets' orbital altitude and not the propellant required for the OTV to travel to and from the asset.

The altitude maintenance propellant requirements analysis presumes a reference altitude of 400 km for purposes of estimating mean atmospheric density. At this altitude, the analysis uses a reference ΔV of 24.3 m/s per year to maintain altitude. The following flowchart (Figure 8) shows the general methodology used to determine the propellant required for the reboost maneuver.

F IGURE 8: LEO R EBOOST P ROPELLANT R EQUIREMENTS A NALYSIS
M ETHODOLOGY

```
┌─────────────────────┐
│   Forecast Mass of  │
│  Emerging Markets   │
└─────────────────────┘
           │
           ▼
┌─────────────────────┐
│ Determine the # of Self │
│ Sufficient Platforms │
└─────────────────────┘
           │
           ▼
┌─────────────────────┐
│ Assuming Each Platform │
│ Requires One OMV for │
│ Reboost, Determine the # │
│  of OMV Reboosts    │
│  Required Each Year │
└─────────────────────┘
           │
           ▼
┌─────────────────────┐
│    Calculate the    │
│  Propellant Required │
│ per Year Based on an │
│ Annual Delta V of 24.3 │
│         m/s         │
└─────────────────────┘
           │
           ▼
┌─────────────────────┐
│  Calculate the LOX and │
│ LH2 Required Based on │
│ 6:1 Oxidizer to Fuel Ratio │
└─────────────────────┘
```

The emerging markets were forecast in pounds launched per year. To determine the number of units on orbit, the market was subdivided into two types of markets: those with interconnecting modules (like the ISS) that would require one OMV per unit, and those markets for which each launch is self-sufficient and therefore would require one OMV per launch. In order to determine the number of units on orbit, an assumption was made that the average unit mass of the interconnecting modules (e.g., the average mass of the complete asset) would be that of the ISS (802,998 lbs). Therefore the total number of OMV reboosts required each year is the sum of the number of interconnecting unit assets and the number of self-sufficient modules.

Markets with interconnecting modules:
- Theme Park
- LEO Business Park
- Space Testbed
- Utilities
- Space Solar Power

Markets with self-sufficient modules:
- Space Manufacturing
- Orbiting Movie Studio
- Space Athletic Event

In order to calculate the propellant required per year, the propellant mass formula is followed:

$$m_{pr} = m_d \, [e^{(\Delta V / I_{sp} g)} - 1]$$

where:

m_{pr} = mass of propellant required to reboost

m_d = dry mass =
    on-orbit mass + [# of OMVs * dry mass of the Delta IV H (3490 kg)]

ΔV = 24.3 m/s per year = mean ΔV (in m/s) required to maintain altitude in a
    400 km circular equatorial orbit[6]

I_{sp} = 462.4 sec, specific impulse

g = 0.0098 m/sec^2 , Earth's gravitational acceleration constant at sea level

PROPELLANT FORECAST

The following graph shows the aggregate propellant forecast through 2020; commercial, government and emerging markets (at $1000/lb) have been included. The depot faces an average annual propellant mass requirement of 1 million kg, with a standard deviation of 245,000 kg. Based on a 6:1 oxidizer to fuel mass ratio, 86% of this mass is LOX and 14% is LH2, which relates to 860,000 kg LOX and 140,000 kg of LH2.

This forecast represents the minimum propellant required to service these markets if these markets relied fully on the depot for the indicated maneuvers. Actual propellant required to fully meet market needs would be in excess of the amount indicated here to accommodate OTV "fetching" of GSO satellites from their initial LEO orbits, orbital plane changes, and the ferrying of the OMV to and from the as of yet undetermined orbits of the emerging market assets.

FIGURE 9: PROPELLANT FORECAST 2001-2020
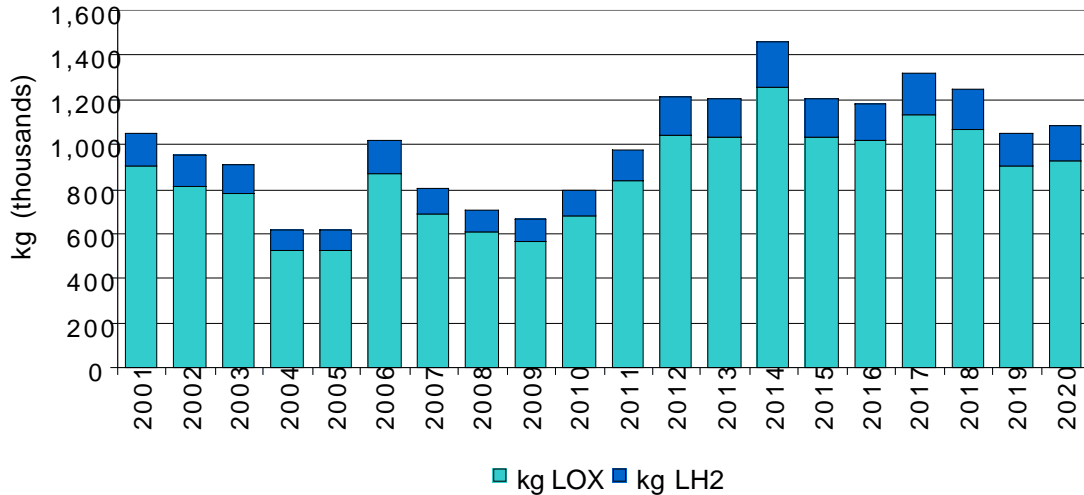
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
kg LOX	901,668	813,004	778,866	524,180	527,211	870,235	690,528	604,579	569,331	683,837
kg LH2	150,278	135,501	129,811	87,363	87,869	145,039	115,088	100,763	94,889	113,973

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[6] Presumes a ballistic coefficient (m/ C_DA) of 100 kg/m2 [$\Delta V = \pi(C_D A/m)\rho r V/P$, where r=6778 km, ρ=2.62 x 10^{-12} (mean atmospheric density at 400 km altitude), P=1.76 x 10^{-4} years (orbital period), V=7.669 km/s (circular velocity)] C_D = coefficient of drag.

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
kg LOX	839,565	1,040,401	1,034,716	1,252,940	1,033,857	1,015,763	1,133,659	1,069,231	899,363	926,010
kg LH2	139,927	173,400	172,453	208,823	172,309	169,294	188,943	178,205	149,894	154,335

FIGURE 10: GOVERNMENT GSO TRANSFER PROPELLANT FORECAST 2001-2020
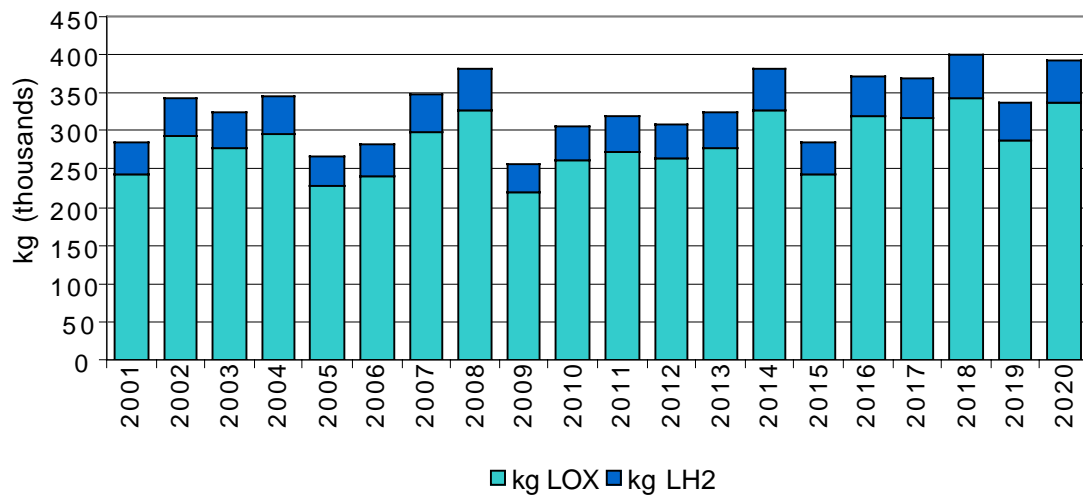
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
kg LOX	244,236	293,303	277,332	295,498	228,356	241,623	298,110	326,399	220,845	262,402
kg LH2	40,706	48,884	46,222	49,250	38,059	40,271	49,685	54,400	36,808	43,734

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
kg LOX	272,525	265,014	277,332	326,399	244,236	318,888	316,694	342,279	288,405	337,472
kg LH2	45,421	44,169	46,222	54,400	40,706	53,148	52,782	57,047	48,067	56,245

FIGURE 11: COMMERCIAL GSO TRANSFER PROPELLANT FORECAST 2001-2020
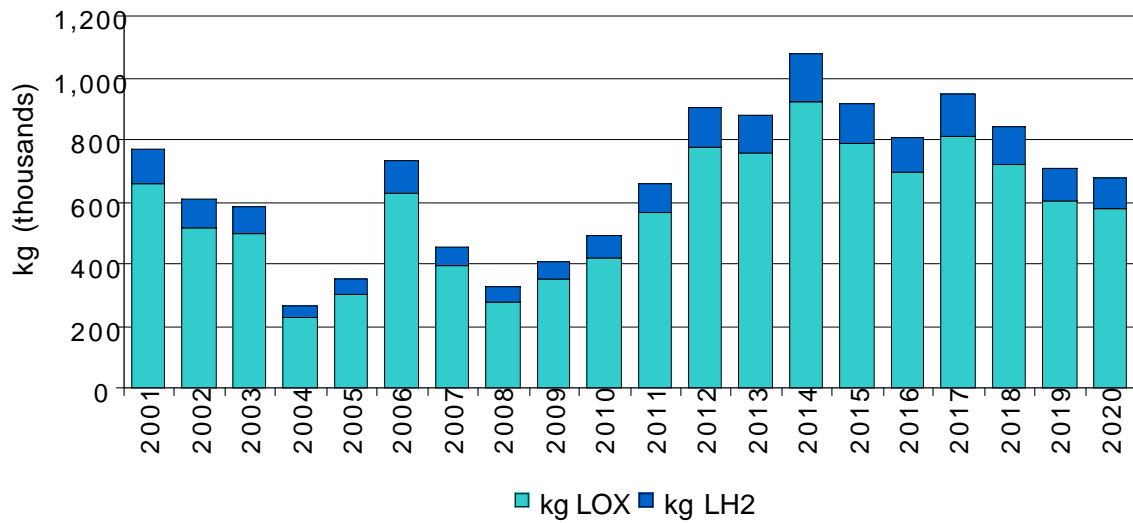
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
kg LOX	657,432	519,700	501,534	228,683	298,855	628,612	392,418	278,077	348,249	421,034
kg LH2	109,572	86,617	83,589	38,114	49,809	104,769	65,403	46,346	58,042	70,172

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
kg LOX	566,277	774,181	755,689	924,323	786,591	693,028	812,268	721,317	604,363	580,972
kg LH2	94,380	129,030	125,948	154,054	131,098	115,505	135,378	120,220	100,727	96,829

FIGURE 12: EMERGING MARKETS PROPELLANT FORECAST 2001-2020 AT $1000/POUND
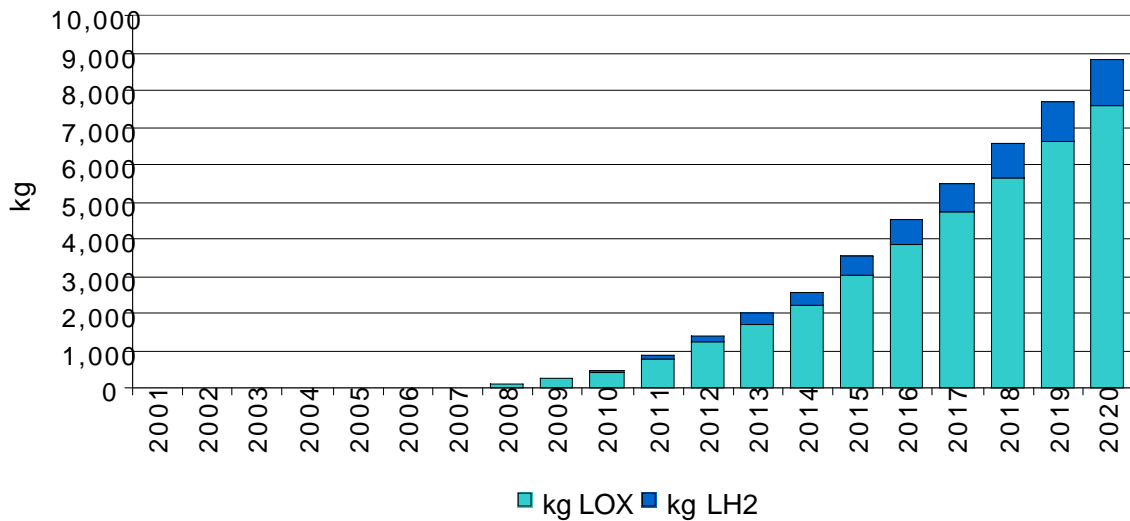
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
kg LOX	0	0	0	0	0	0	0	103	237	401
kg LH2	0	0	0	0	0	0	0	17	40	67

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
kg LOX	763	1,205	1,695	2,217	3,030	3,846	4,697	5,635	6,595	7,565
kg LH2	127	201	282	370	505	641	783	939	1,099	1,261

FIGURE 13: EMERGING MARKETS PROPELLANT FORECAST 2001-2020 AT $500/POUND
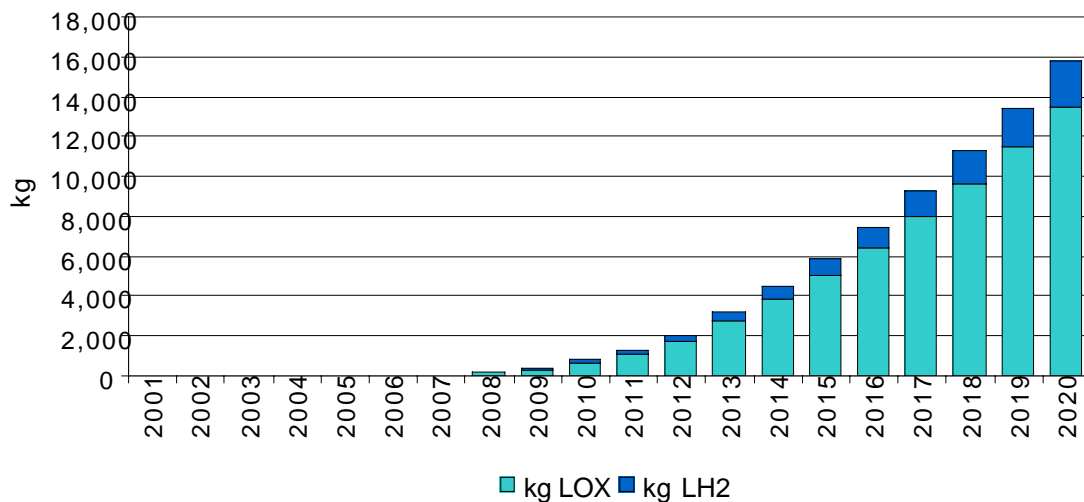
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
kg LOX	0	0	0	0	0	0	0	138	285	687

| kg LH2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 23 | 47 | 115 |

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
kg LOX	1,129	1,745	2,719	3,841	5,054	6,387	7,950	9,644	11,497	13,542
kg LH2	188	291	453	640	842	1,064	1,325	1,607	1,916	2,257

ON-ORBIT ELECTROLYSIS

This analysis is based on a propellant depot that receives, stores, and transfers cryogenic propellants; however in the case that on-orbit electrolysis becomes a viable alternative, the amount of water required for delivery to the depot to meet the above-calculated propellant requirements can be determined based on the stoichiometric relationship for water, which is 8:1 (Oxygen:Hydrogen).

FIGURE 14: WATER (H_2O) FORECAST 2001-2020 FOR THE GSO SATELLITE TRANSFER AND PLATFORM ORBITAL REBOOST AT $1000/LB PRICE POINT
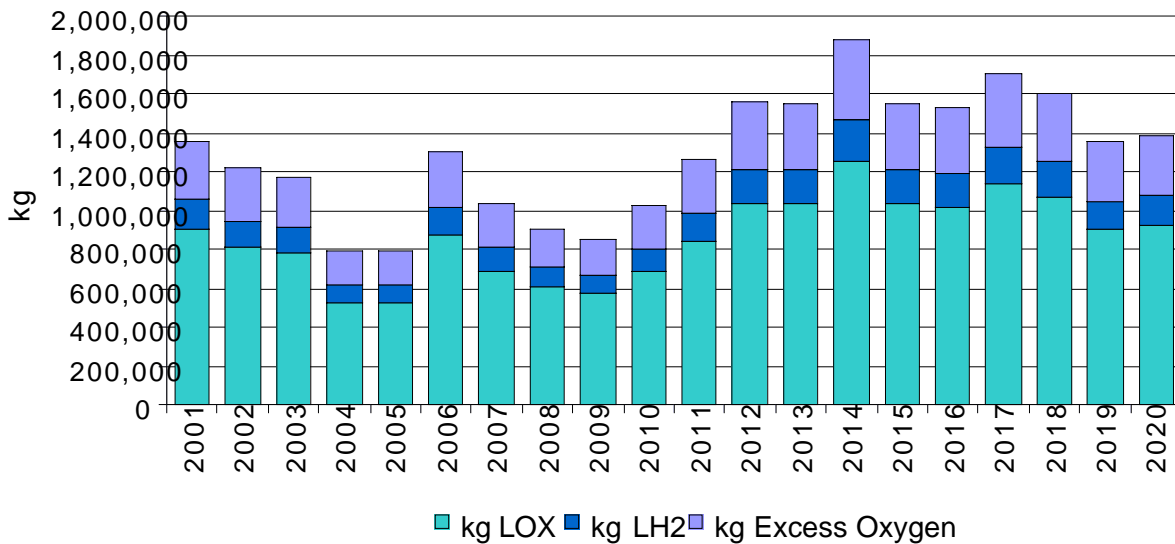
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
LOX	901,668	813,004	778,866	524,180	527,211	870,235	690,528	604,579	569,331	683,837
LH2	150,278	135,501	129,811	87,363	87,869	145,039	115,088	100,763	94,889	113,973
Excess Oxygen	300,556	271,001	259,622	174,727	175,737	290,078	230,176	201,526	189,777	227,946
Water	1,352,502	1,219,505	1,168,299	786,270	790,817	1,305,353	1,035,792	906,869	853,997	1,025,755

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
LOX	839,565	1,040,401	1,034,716	1,252,940	1,033,857	1,015,763	1,133,659	1,069,231	899,363	926,010
LH2	139,927	173,400	172,453	208,823	172,309	169,294	188,943	178,205	149,894	154,335
Excess Oxygen	279,855	346,800	344,905	417,647	344,619	338,588	377,886	356,410	299,788	308,670
Water	1,259,347	1,560,601	1,552,074	1,879,409	1,550,785	1,523,644	1,700,488	1,603,846	1,349,045	1,389,014

CONCLUSIONS

Communications satellites will present the single largest market opportunity for a propellant depot, generating a steady demand for approximately 700,000 kg of propellant annually. In addition, the government GSO market will continue at an average of $^1/_3$ to _ the commercial GSO market throughout the forecast period. The markets assessed here represent LOX/LH2 propellant demand more than twice the annual propellant requirements for the most propellant-intensive human Mars mission scenario.[7] Over the next twenty years, communication satellites will continue to dominate the space industry, despite investment to bring down the cost of space access. Even if launch costs were to drop to $500/lb to LEO, emerging non-satellite markets would constitute only about 1.5 percent of the propellant requirements forecasted here.

Depot technical specifications and choice of fuel affect the services available to the orbital assets. A bipropellant LOX/LH2 depot, as analyzed here and put forth as the choice to enable a human Mars mission, would likely be constrained to offering the space "tug" services identified here. Alternatively, a monopropellant depot could offer refueling options for satellite on-board station-keeping thrusters. The lower specific impulses of monopropellants, however, make this option a less desirable alternative for high ΔV maneuvers, such as GSO transfer.

Regardless of the technical specifications of the selected depot, any realization of the markets identified both qualitatively and quantitatively in this report would require concerted coordination between depot and orbital tug developers and the satellite manufacturers themselves. The system interface requirements are extensive, necessitating significant commitments by all parties over a lengthy development schedule. Moreover, reliance on an orbital tug introduces a measure of risk and uncertainty into the business plans of satellite manufacturers and operators for which savings or revenues must aggressively compensate.

This analysis sets the stage for an overall assessment of the economic arguments for and against an in-space propellant depot. The costs of building, servicing, and fueling a depot should be contrasted against the economic value the depot brings to its customer base. Such an analysis should include an explicit treatment of the business case risks inherent in the introduction of depot reliance to traditional space businesses such as satellite communications.

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[7] The Boeing Corporation, *Space Solar Power and Platform Technologies for an In-space Propellant Depot.*

APPENDIX A

Propellant depots could take on a variety of forms. For this analysis we looked at just one configuration, but others might introduce opportunities to meet alternative markets. Depot choice and state of propellant, the configuration of their interfaces with orbital assets, their orbital location, and their source of fuel could distinguish depots. These design choices have a significant impact on the markets a depot could optimally serve.

A monopropellant depot could address a potentially large communications satellite refueling market. A bipropellant depot with a high specific-impulse fuel, as treated in this report, might service the significant LEO to GSO transfer market if satellite manufacturers and operators embraced the depot concept. A water-to-cryogen depot might serve the propellant, fuel, and radiation protection outfitting requirements of a human interplanetary transport vehicle.

Along another vein, the ready ability to refuel a satellite in orbit could introduce a level of flexibility heretofore unheard of for satellite missions. For national security applications in particular, the constraints of satellite flight paths limit information availability for time-critical events. If refueling were a ready option, on-board fuel reserves might be spent to maneuver a satellite to a more desirable orbit in order to cover an identified hot spot or event more effectively. Because the satellite could be refueled, such a maneuver need not have an impact on overall satellite lifetime and utility. The same scenario could be applied to civilian remote sensing satellites to enable them to cover environmental phenomena or natural disasters at the optimal time of day.

At some point in the future, space travel and activity will become commonplace enough to merit fuel depots in space. As our space vehicles themselves become durable goods held for the long term, in-space propellant depots will arise just as gas stations arose to serve the growing automobile market in the early twentieth century. The propellant source for these depots need not be Earth. We might mine captured comets, icy asteroids, or lunar regolith for oxygen and hydrogen. Depots might orbit the Moon and Lagrangian points, or act as refineries amongst the Asteroid belt.

Figure A1 summarizes a broad range of potential depot markets and includes pertinent depot parameters necessary to meeting those markets. The figure also provides an approximate time frame for market realization.

FIGURE A1: A SURVEY OF POTENTIAL DEPOT MARKETS
(*QUANTITATIVE ASSESSMENT IN MAIN REPORT)

Market	Propellant type	Propellant source	Depot orbit	Realization timeframe[8]
*GSO Tug (commercial, government, and emerging markets' GSO assets)	Bipropellant (LOX/LH2)	Launch from Earth	LEO	Near term
*Platform Reboost	Bipropellant	Launch from Earth	LEO	Near term
Satellite Station Keeping	Monopropellant (Hydrazine)	Launch from Earth	LEO	Near term
Satellite Recovery	Mono or Bipropellant	Launch from Earth	LEO	Near term
Orbital Plane Changes	Monopropellant	Launch from Earth	LEO	Near term
Satellite Imaging System Cryogen Coolant Resupply	Bipropellant	Launch from Earth	LEO	Near term
Transport Vehicle Fueling	Bipropellant	Launch from Earth	LEO	Near to Mid term
Transport Vehicle Water Outfitting (potable water, radiation protection)	Bipropellant (water derivative)	Launch from Earth	LEO	Mid term
Crewed Vehicle Oxygen Outfitting	Bipropellant	Launch from Earth	LEO	Near to Mid term
Earth-Moon Transport Fueling	Bipropellant	Mined from Moon	Lunar orbit	Mid term
Mining Transport Fueling (General Vehicle Fueling)	Bipropellant	Mined from Asteroid belt	Asteroid belt	Far term

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[8] Potential realization timeframe from a technical standpoint.
   Near term < 20 years
   20 years < Mid-term < 40 years
   Far-term > 40 years